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COMPARISON OF CONSTANT CURRENT AND CAPACITOR DISCHARGE IGNITION OF NORMAL LEAD STYPHNATE

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ABSTRACT: A comparison was made of constant current and capacitor discharge ignition of normal lead styphnate in the time regime typically employed for firing initiators by each type of signal. The loading pressure was varied from 2,500 to 60,000 psi. For the regimes studied, as the explosive loading pressure was increased, constant current activation gave longer ignition times but capacitor discharge firing gave shorter ignition times. The energy requirement for ignition increased with loading pressure for constant current ignition, and was constant for capacitor discharge ignition.

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This report compares the effects of constant current and capacitor discharge activation signals (used in their typical time regimes) on the ignition of normal lead styphnate over a range of loading pressures. The work was performed under task ORD 332 001/UF17 354 314 Problem 201, Explosive Initiation and Safety.

The results should be of interest to persons engaged in initiation research and in the design of electrical initiators and power supplies therefor.

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INTRODUCTION

1. The effective utilization of explosives and explosive trains requires a thorough understanding of the initiation process and the growth of explosion. Many factors affecting the initiation of explosives in explosive components have still not been explained. Further studies of these factors, both chemical and physical, is needed in order to build safe, reliable, and effective fuze trains.

2. There is increasing interest in the effect of various electrical activation signals upon thermally activated electro explosive devices (EED's). For example, military specification MIL-I-23659 for insensitive EED's places upper (all fire-5 amperes, 50 milliseconds) and lower (no fire-1 ampere, 5 minutes) limits on the constant current sensitivity, making the constant current characteristics and functioning times of designer interest.[1] EED's meeting the above requirements must sometimes be fired by capacitor discharge firing circuits, thereby also generating interest in the pulse firing characteristics and functioning times.[2]

3. Normal lead styphnate (NLS) is probably the most widely used ignition material in EED's. Although considered a relatively poor initiating material, NLS is easily ignited by a hot wire and has good storage properties.

4. The effects of loading pressure on the hot wire ignition of normal lead styphnate by capacitor discharge have been previously investigated.[3] It was found that the capacitor discharge energy requirement of NLS remains fairly constant over a wide loading pressure range and the average ignition time decreases as the loading density in increased. In this report, the effects of loading density on the constant current ignition of NLS are examined and a comparison is made with the capacitor discharge ignition results. The investigation was made with a wire size typical of current EED use, and the results are believed to be applicable to larger diameter wires used in insensitive EED's.

EXPERIMENTAL

5. The effect of loading density on the constant current ignition time and energy requirement of NLS was investigated at three loading pressures - 2,500 psi, 10,000 psi, and 60,000 psi. The time of ignition was determined by two separate techniques - the "voltage inflection technique"[4,5] and the "light pipe technique"[6] - so that a comparison could be made of the two methods. Results were also compared with those obtained previously by capacitor discharge.[3]

6. Firing Circuit - A d.c. power supply in conjunction with a mercury wetted millisecond switch was used to produce the constant current pulse.[7] The circuit contains a 15-ohm ballast resistor. A constant current level of 0.3 ampere was used for ignition because this value gives ignition times within the control period of the switch and will not burn out the bridgewire during the time region of interest. An equivalent resistor (within 0.25 ohm of the bridgewire resistance to be tested) was first substituted before each shot to regulate to the desired current level of 0.3 ampere.

7. Initiator Plug - A specially modified initiator plug was used for loading the explosive on the bridgewire. A hole was drilled axially through the initiator plug between the two contact pins, and a light pipe potted in this hole so that radiation from the initial reaction of the explosive could be detected and transmitted to a photodetector tube. See Fig. 1. The light pipe method is described fully in NOLTR 69-148. The plug is bridged with a 1-mil diameter nichrome wire having an effective length of 0".050 after soldering to the contact pins. This bridgewire has a resistance range of 2.5 to 4.0 ohms.

8. Recorder - A Tektronix 555 Dual-beam Oscilloscope with two fast-rise, Type K preamplifiers was used to observe the voltage across the wire and the photodetector tube signal. The voltage inflection technique for determining the ignition time requires no special equipment other than a means of monitoring the voltage (IR drop) across the bridgewire during the current pulse. In addition to determining the time of ignition, the observed voltage change was employed to determine the bridgewire temperature. For this latter purpose it is difficult to make precise measurements of the voltage change across the wire when the entire signal amplitude is observed, since there is only a 4-8% increase in resistance before ignition occurs. Figure 2A shows the voltage signal obtained with a bare

bridgewire using a 72 millisecond duration pulse. In order to amplify the voltage change in the signal by using a high oscilloscope sensitivity, the beam spot must be set well below the viewing screen, then only the signal portion of interest is observed. See Fig. 2B. A variable bucking voltage can be employed if necessary to lower the beam spot if the oscilloscope vertical position dial does not provide sufficient latitude.

RESULTS

9. Constant current pulses of 0.3-ampere amplitude maintained for a longer period than necessary for firing, were used to fire ten loaded initiator plugs at each of the three loading pressures. The ignition times were observed by the "voltage inflection technique" and the "light pipe technique". The two methods were found to corroborate each other, indicating the same ignition time within the resolution of the millisecond sweep speeds. See Fig. 3A. The average time of ignition was found to increase markedly and the calculated temperature* of the bridgewire at the time of ignition to drop with increasing loading pressure. See Table I.

10. Several of the wire temperature excursions were observed to be quite irregular when subjected to a constant current pulse. See Fig. 3B. Prepulsing of all the test initiator plugs before loading was used to minimize the irregular changes. Prepulsing of the bridgewire with a 0.5-microfarad capacitor charged to 50 volts before loading of the explosive tends to produce a more linear resistance change, but does not entirely remove the irregularities. Irregularities were found to be more prevalent at the 2,500-psi loading pressure and drop off as the loading pressure is increased. No irregular resistance changes were observed at the 60,000-psi loading pressure. From this observation, one might surmise that the irregularities are largely due to stress relief from wire movement during the heating, and/or changes in thermal contact with the explosive.

* Calculated from wire resistance, assuming linear increase of resistance with temperature in observed region.

DISCUSSION

11. The sensitivity of electro explosive devices has conventionally been determined by capacitor discharge or constant current input.[8] Capacitor discharge circuits are usually employed where a rapid rate of energy input is desired. This is accomplished by making the RC discharge time short in comparison to the cooling time of the bridgewire. Usually the RC time is in the microsecond region. Constant current pulses are usually not employed in the low microsecond region because of the difficulty of shaping and regulating a high amperage square wave pulse. Typical of constant current values might be those employed by Mallory and Goss[5] who used a current pulse which can be varied in duration from 1 to 3 milliseconds and in amplitude from 0.1 to 1 ampere. Larger amplitude and longer duration pulses have recently been employed for the testing of insensitive EED's. The values herein are fairly typical of those used for the capacitor discharge and constant current waveshapes.

12. In examining the effect of loading density upon the hot wire ignition time of NLS, the ignition time was found to increase with increasing density when the constant current pulse was used to heat the wire. In previous work it was found that the ignition time decreases with increasing density when using a capacitor discharge to heat the wire.[3] See Fig. 4. It can be seen then that the loading density-ignition time effect is dependent upon the type of electrical firing signal. A discussion follows on the two types of electrical activation signals.

13. <u>Constant Current</u> - Under conditions where the bridgewire remains intact when heated by a constant current pulse, the bridgewire at first heats up rapidly and then asymptotically approaches a limiting temperature as equilibrium conditions are approached. See Fig. 3A. The power input (P) to the wire during the constant current (I) pulse will rise according to

$$P = I^2 R_0 (1 + \alpha T) \quad .$$

R_0 is the initial resistance, α the thermal coefficient of resistance, and T the temperature rise. The current levels commonly employed for constant current firing give initiation under non-adiabatic conditions - in the millisecond time region - and that is true of the work reported here.

14. When the explosive is poorly coupled (low density) to the nichrome bridgewire, keeping the radial loss of heat from the wire at a low rate, the resistance rise due to heating effects will occur at a relatively rapid rate. See Fig. 5. Therefore, the power input to wires in contact with low density explosive will increase more rapidly than to wires in good thermal contact with the explosive. The low density explosive will conduct heat away from the bridgewire at a low rate due to its poor thermal contact to both the wire and with itself. One might then anticipate that the fast bridgewire heating observed with low density explosive, coupled with the poor heat transmission through the low density explosive will cause ignition of a critical volume of NLS much more rapidly than a wire in good contact with the explosive. This is observed to occur even though a higher ignition temperature exists for the explosive due to the shorter period of heat exposure.

15. An important controlling factor appears to be heat conduction through the explosive away from the granules adjacent to the wire. See Table II. The table indicates that under the non-adiabatic conditions of the constant current pulse, the heat loss is an important factor in determining the probability and time of ignition. Of interest to the present study is a paper by Austing and Weber who in the examination of the constant current ignition of metal-metal oxide mixtures noticed that increases in density increased the time to ignition.[9] Even though the thermal conductivity of NLS is approximately three magnitudes lower than the metal-metal oxide mixtures, the heat transmission is sufficiently affected by the loading density to exhibit the same type of effect.

16. In constant current initiation the longer the required period of current flow, the greater the energy requirement. Therefore, the denser the NLS, the greater the ignition energy requirement in the non-adiabatic time region.

17. Capacitor Discharge - During a capacitor discharge, for the experimental parameters used, the wire heats rapidly, reaching the maximum temperature near the end of the discharge. It then undergoes a comparatively long cooling cycle. See Fig. 6. The NLS can ignite either during the course of the temperature rise or during the cooling period of the wire. In the present constant current tests however, ignition must occur during the temperature rise since the pulse length was made intentionally longer than the ignition time.

18. Capacitor discharge parameters commonly used to effect hot wire initiation usually give initiations in the microsecond time region. Eyring, et al, in studying heat conduction into a grain of 100 μ diameter have shown the grain surface requires 1 to 10 microseconds to reach the temperature of the heating bath.[10] The center of the grain can remain cool for times up to 100 microseconds.[10] See Fig. 7. The diagrams are for a fully immersed grain. For a comparison with wire heating, one can assume heat entry from only

one surface with a grain thickness of 5 - 10 u. Only the first few layers of explosive adjacent to the wire will be of importance for discharge times in the order of microseconds.

19. Even for the short times involved in a capacitor discharge, the temperature excursion of the bridgewire is dependent upon the degree of coupling to the explosive. A wire poorly coupled to the explosive (low density) will reach a higher temperature and cool at a slower rate than one in good thermal contact with the explosive.[3] This indicates a slower transfer of heat from the wire to the explosive. In general, the poorer the thermal contact, the later the time of ignition due to the slower heat transfer. Even with fairly good coupling, the temperature of the explosive would be expected to lag that of the wire as indicated by the results of Eyring, et al. If ignition does not occur on the temperature rise of the wire, and the wire temperature remains above the ignition temperature of the explosive, heat transfer will continue and ignition can occur during the wire cooling phase. Ignition is possible until the wire temperature drops below the explosive ignition temperature.

20. The energy requirement for the ignition of NLS remains constant over a wide density range even though the heat capacity of the bridgewire system increases with loading pressure. The exact explanation is unknown at this time but it appears to have some connection with the rate of heat transfer. Greater heat losses to the inert parts appear to occur at the lower densities because of the slower heat transfer to the explosive, thereby equalizing the energy requirement over a wide density range.

21. Implications - It can be surmised from the above discussions that for fast rates of energy input the thermal contact resistance between the wire and the explosive is of prime importance while for slow rates of energy input, the energy input rate in comparison to the cooling time is of prime importance. It is well known in capacitor discharge work that as the capacitance is increased and the firing voltage decreased, more energy is required for firing since the initiation process becomes non-adiabatic. Conversely, as the constant current level is increased, the initiation process approaches an adiabatic condition and less energy is necessary. The phenomena observed therefore, cannot be attributed to the type of waveform used, but to the time regime in which each waveform is typically employed. One would therefore expect that as the input times from the two types of electrical signals approach each other at some intermediate time region, density effects upon the ignition time would gradually lessen because of the opposing tendencies with perhaps the cooling effect predominating.*

*Measured cooling time constants for the experiments reported here are 2600 microseconds at 2.5-K psi loading pressure and 1400 microseconds at 60-K psi loading pressure. Thermal lag effects appear to be important up to 100 microseconds.

22. The results are of interest in the design of insensitive EED's. They show that the insensitivity of NLS (and most likely other styphnates) to non-adiabatic constant current ignition can be increased* by increasing the loading pressure and yet not affect the energy sensitivity to capacitor discharge. The occurrence of faster ignition times with capacitor discharge initiation as the loading pressure is increased would in most cases be considered a favorable condition.

23. Analysis of hot wire initiation is sometimes limited to a study of the bridgewire temperature history. It can be seen from the constant current results that the relationship between the bridgewire temperature and the probability of initiation can be somewhat tenuous over an experimental parameter range (i.e., density) where ignition temperatures varying from 339 to 450°C were derived from the wire resistance change. The relationship between the bridgewire temperature and the probability of initiation depends upon such diverse factors as thermal contact resistance, variation of explosive initiation temperature with time of exposure to heat source, radial loss of heat, and particle size of the explosive. The bridgewire temperature has been successfully used for mathematical predictions based upon a specific set of conditions, but care should be taken when there is any parameter variance.

*A five to one constant current energy increase was effected under the experimental conditions. See Appendix A for supplemental tests with an insensitive bridge element.

CONCLUSIONS

24. The effect of loading density on the ignition of NLS depends upon the type of electrical activation signal. For very short activation times (microsecond region) the thermal contact resistance between the bridgewire and the explosive appears to be of prime importance. For longer input times (millisecond region), heat loss through the explosive appears to be the prime consideration.

25. The time of ignition and energy requirement of NLS will increase with increasing density when employing a constant current pulse in its typical time regime (non-adiabatic region). This technique can be employed to assist NLS to meet the 1-amp/1-watt no-fire requirement of MIL-I-23659.

26. At high constant current inputs (ca. 5 amperes) where adiabatic conditions are being approached, changes in the density of NLS have a negligible effect upon the time of ignition and energy requirement.

27. Studies relating the bridgewire temperature to the probability of initiation should be carefully examined when any parameter is varied.

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TABLE I

EFFECT OF LOADING PRESSURE ON CONSTANT CURRENT (0.3 AMPERE)

IGNITION CHARACTERISTICS OF NORMAL LEAD STYPHNATE

Loading Pressure (K psi)	Average Time of Ignition (msec)	Average Bridgewire Resistance Change (%)	Average Calculated Bridgewire Temperature* Rise (°C)	Energy Approximation** (Ergs)
2.5	25.8	6.47	430	73,000
10.0	51.1	5.87	392	141,000
60.0	143.0	4.78	319	382,000

* Temperature calculated by obtaining ΔR from the voltage change observed on the oscillogram and using a temperature coefficient of resistance of 150 parts per million.

** Based on ambient average resistance for each loading pressure I^2R_0t). These values are a few percent low since the resistance increase has not been taken into account.

TABLE II

ENERGY DIVISION FROM CONSTANT CURRENT PULSE

NLS Loading Pressure (K psi)	Delivered Energy Approximation* (Ergs)	Temperature Elevation of Wire at time of Ignition (°C)	Energy Required For Temperature Elevation of Wire (Ergs)	Energy Loss to Surroundings (Ergs)	Energy Loss / Energy Delivered (%)
2.5	73,000	430	11,500	61,500	84
10.0	141,000	392	10,500	130,500	93
60.0	382,000	319	8,520	373,480	97.5

* I^2R_0t .

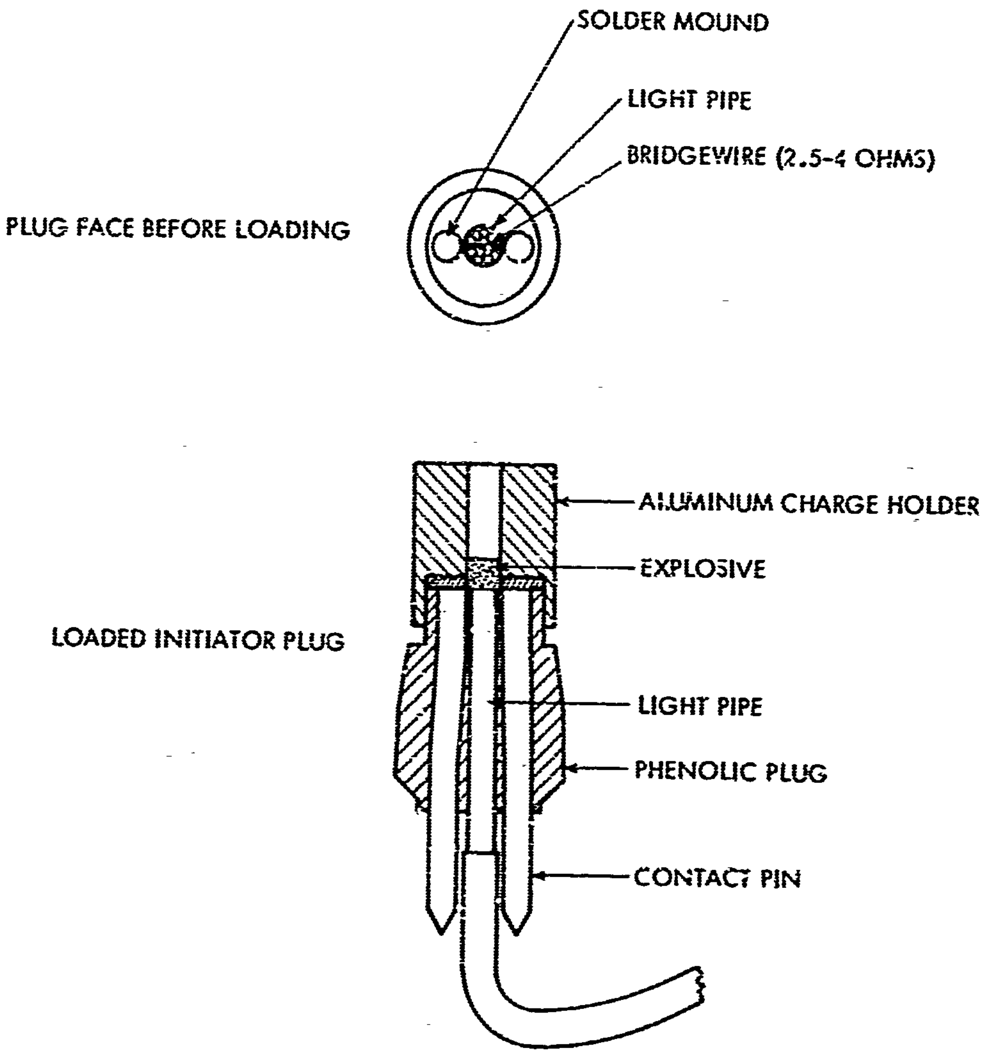
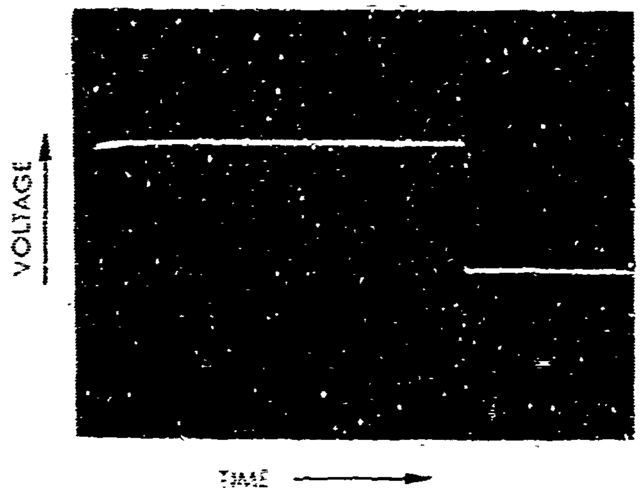


FIG. 1 MODIFIED INITIATOR PLUG



SWEEP SPEED - 10 MILLISECONDS/ DIV
VERTICAL SENS - 0.5V/ DIV

A. ENTIRE SIGNAL

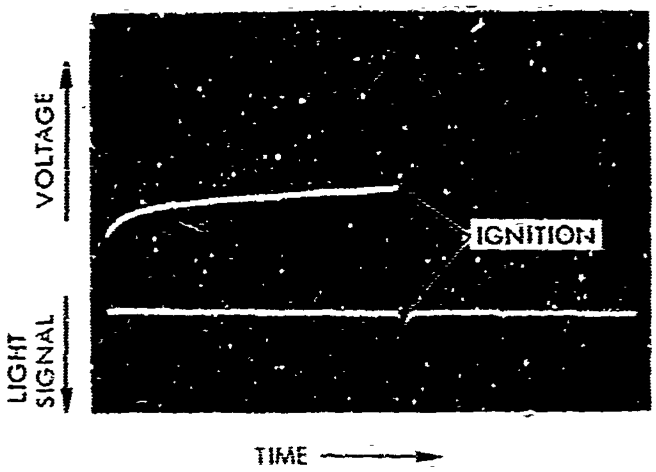
NOT REPRODUCIBLE

SWEEP SPEED - 10 MILLISECONDS/ DIV
VERTICAL SENS - 0.05V/ DIV

TIME

B. AMPLIFIED SECTION

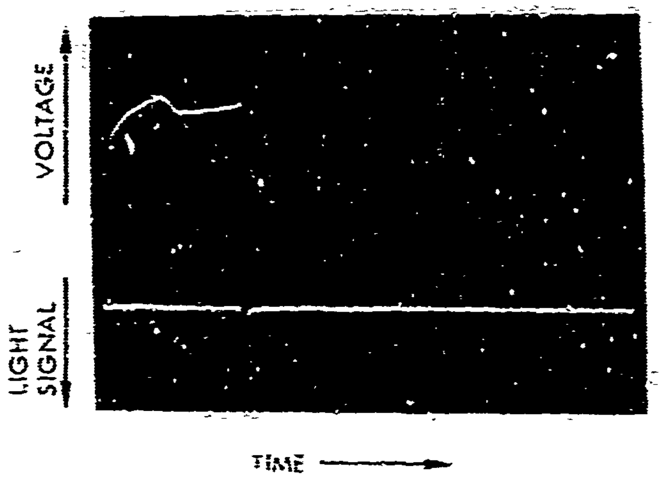
FIG. 5 AMPLIFICATION OF VOLTAGE SIGNAL ACROSS BRIDGEWIRE



SWEEP SPEED - 20 MILLISECONDS/DIV
60,000 PSI LOADING PRESSURE

(A) TYPICAL VOLTAGE DROP WITH IGNITION OCCURRING

NOT REPRODUCIBLE



SWEEP SPEED - 10 MILLISECONDS/DIV
2,500 PSI LOADING PRESSURE

(B) IRREGULAR VOLTAGE DROP WITH IGNITION OCCURRING

FIG. 3 EXPERIMENTAL OSCILLOGRAMS

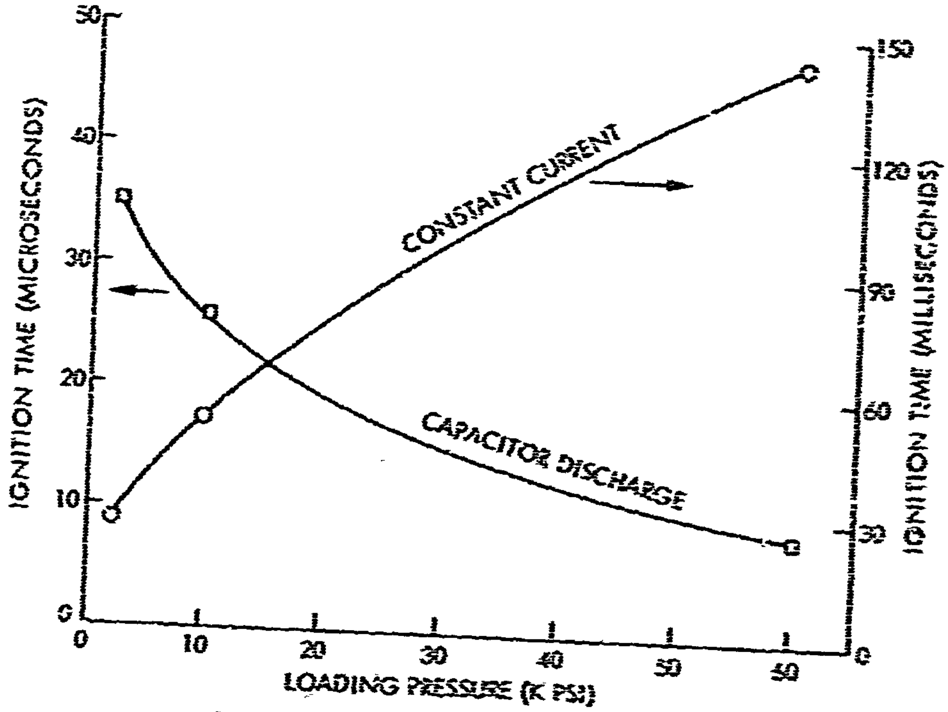


FIG. 4 EFFECT OF LOADING PRESSURE ON IGNITION TIME OF NORMAL LEAD STYPHNATE BY CONSTANT CURRENT AND CAPACITOR DISCHARGE SIGNALS IN THEIR TYPICAL TIME REGIMES

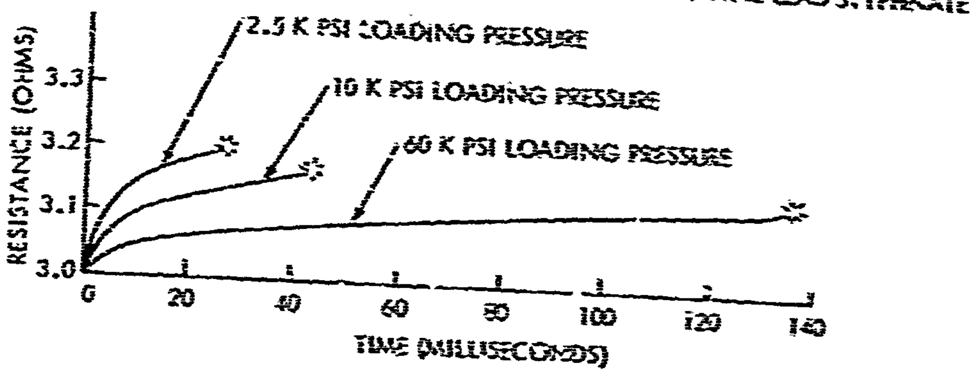


FIG. 5 TYPICAL RESISTANCE CHANGES DURING CONSTANT CURRENT PULSE

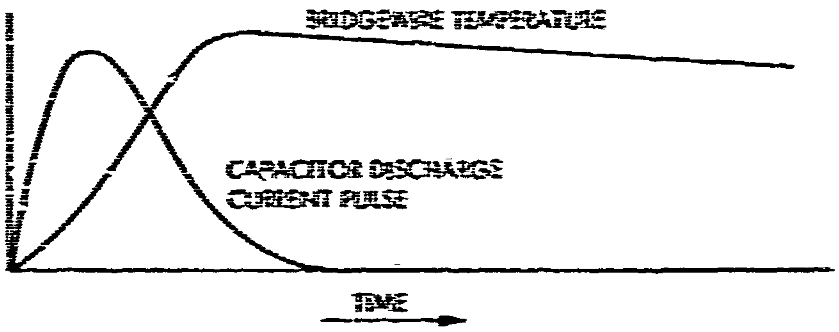


FIG. 6 RELATIONSHIP OF BRIDGEWIRE TEMPERATURE TO CAPACITOR DISCHARGE PULSE

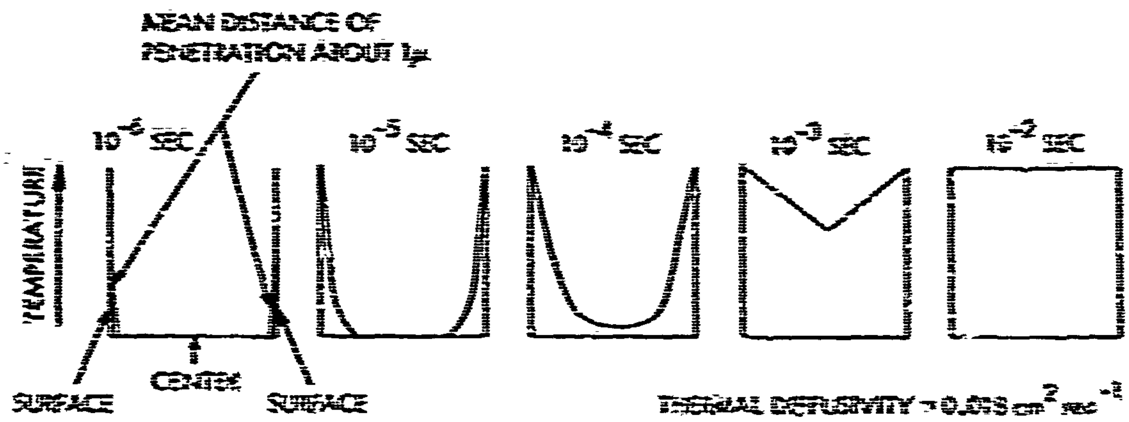


FIG. 7 DISTRIBUTION OF TEMPERATURE IN A SPHERE OF DIAMETER 100μ, HEATED AT THE SURFACE (AFTER EYRING et al.[10])

APPENDIX A

A.1. The effect of loading pressure on the sensitivity of NLS with the Mk 101 type 1-amp/1-watt ribbon bridge[2] was briefly examined to determine if the investigation results were applicable to actual hardware. The plug element only was employed in these tests. It consists of the glass/kovar plug, the evanohm bridge element, plastic insulator, and aluminum charge holder. See Table A-I.

A.2. The results in Table A-I show that the insensitivity of NLS can be increased at the lower current levels (non-adiabatic region) by increasing the loading pressure. At the 5-ampere "all fire level", the increase in insensitivity is negligible (as one would expect when approaching adiabatic conditions) and the ignition time will be well within the 50 millisecond functioning requirement of MIL-I-23659.

TABLE A-I

CONSTANT CURRENT TEST RESULTS FOR NLS ON

1-AMPERE/1-WATT RIBBON BRIDGE

Current (amps)	Loading Pressure (K psi)	Resistance (ohms)	Time of Current Flow	Results
1.2	10,000	1.24	5.0 mins	No fire
1.2	10,000	1.26	0.82 "	Fired
1.2	10,000	1.27	1.48 "	Fired
1.2	10,000	1.28	0.55 "	Fired
1.2	10,000	1.28	2.87 "	Fired
1.2	60,000	1.23	5.0 mins	No fire
1.2	60,000	1.27	5.0 "	No fire
1.2	60,000	1.28	5.0 "	No fire
1.2	60,000	1.28	5.0 "	No fire
1.2	60,000	1.28	5.0 "	No fire
5.0	10,000	1.27	4.3 msec	Fired
5.0	10,000	1.29	2.6 "	Fired
5.0	10,000	1.31	2.6 "	Fired
5.0	60,000	1.27	2.9 msec	Fired
5.0	60,000	1.28	2.7 "	Fired
5.0	60,000	1.29	6.2 "	Fired

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13. ABSTRACT

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Hot wire						
Normal Lead Styphnate						
Ignition						
Initiation						

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